Mon. Not. R. Astron. Soc. **000**, 1–12 (2006) Printed 3 February 2008 (MN LaTeX style file v2.2)

Rejuvenation of spiral bulges

Daniel Thomas[1,2] & Roger L. Davies[1]
[1]*University of Oxford, Denys Wilkinson Building, Keble Road, Oxford, OX1 3RH, UK*
[2]*Max-Planck-Institut für extraterrestrische Physik, Giessenbachstraße, D-85748 Garching, Germany*

Accepted 2005 November 15. Received 2005 November 2; in original form 2005 September 23

ABSTRACT
We seek to understand whether the stellar populations of galactic bulges show evidence of secular evolution triggered by the presence of the disc. For this purpose we re-analyse the sample of Proctor and Sansom, deriving stellar population ages and element abundances from absorption line indices as functions of central velocity dispersion and Hubble type. We obtain consistent constraints on ages from the three Balmer line indices Hβ, Hγ, and Hδ, based on stellar population models that take the abundance ratio effects on these indices into account. Emission line contamination turns out to be a critical aspect, which favours the use of the higher-order Balmer line indices. Our derived ages are consistent with those of Proctor and Sansom based on a completely different method. In agreement with other studies in the literature, we find that bulges have relatively low luminosity weighted ages, the lowest age derived being 1.3 Gyr. Hence bulges are not generally old, but actually rejuvenated systems. We discuss evidence that this might be true also for the bulge of the Milky Way. The data reveal clear correlations of all three parameters luminosity weighted age, total metallicity, and α/Fe ratio with central velocity dispersion. The smallest bulges are the youngest with the lowest α/Fe ratios owing to late Fe enrichment from Type Ia supernovae. Using models combining recent minor star formation with a base old population, we show that the smallest bulges must have experienced significant star formation events involving $10-30$ per cent of their total mass in the past $1-2$ Gyr. No significant correlations of the stellar population parameters with Hubble Type are found. We show that the above relationships with σ coincide perfectly with those of early-type galaxies. In other words, bulges are typically younger, metal-poorer and less α/Fe enhanced than early-type galaxies, because of their smaller masses. At a given velocity dispersion, bulges and elliptical galaxies are indistinguishable as far as their stellar populations are concerned. These results favour an inside-out formation scenario and indicate that the discs in spiral galaxies of Hubble types Sbc and earlier cannot have a significant influence on the evolution of the stellar populations in the bulge component. The phenomenon of pseudobulge formation must be restricted to spirals of types later than Sbc.

Key words: stars: abundances – Galaxy: abundances – globular clusters: general – galaxies: stellar content – galaxies: elliptical and lenticular, cD

1 INTRODUCTION

Pseudobulges are bulges formed out of disc material in secular processes (Kormendy 1982). As laid out in detail in the recent review by Kormendy & Kennicutt (2004), they are 'are not just dust features or the outer disk extending inside a classical bulge all the way to the centre', but appear to be built by nuclear star formation. In other words, the presence of pseudobulges in spiral galaxies should be detectable through fingerprints of relatively recent star formation in their stellar populations. This seems to stand in clear contrast to the commonly accepted perception that bulges are generally old (Renzini 1999). There is strong and compelling evidence that the bulk of stellar populations in the Milky Way Bulge are old without significant amounts of recent star formation (Ortolani et al. 1995; Renzini 1999; Ferreras et al. 2003; Zoccali et al. 2003). On the other hand, blue colours, patchy dust features, and low surface brightnesses are found predominantly in bulges of later type spirals (de Jong 1996; Peletier et al. 1999). Moreover, bulge colour and disc colour appear to be correlated pointing toward the presence of secular evolution processes (Peletier & Balcells 1996; Wyse et al. 1997; Peletier et al. 1999; Gadotti & dos Anjos 2001). Based on these indications, Kormendy & Kennicutt (2004) conclude that stellar populations are at least consistent with the expectation that the latest type galaxies must have pseudobulges.

The aim of this paper is to look into this in more detail, and to search for fingerprints of recent star formation in bulges by deriving average ages and abundance ratios of bulges along the Hubble sequence. We the use of the α/Fe ratio as a measure for Type Ia supernova enrichment, and hence late star formation. We study the sample of Proctor & Sansom (2002, hereafter

PS02) comprising 32 spheroids in a relatively large range of Hubble types from E to Sbc. By means of abundance ratio-sensitive stellar population modelling (Thomas, Maraston & Bender 2003; Thomas, Maraston & Korn 2004), we derive luminosity weighted ages, metallicities, and α/Fe ratios of the central stellar populations (inner ~ 250 pc) from a combination of metal indices ($\mathrm{Mg}\,b$, Fe5270, Fe5335) and Balmer line indices (Hδ_{A}, Hγ_{A}, Hβ). The resulting stellar population parameters are compared with the results obtained by PS02, and then analysed with two-component models with the aim to quantify the possible contribution of recent star formation on the basis of a generally old population.

An additional constraint will be set by the direct comparison with recent findings on early-type galaxies (Thomas et al. 2005) under the premise that a deviation of bulge properties from those of early-type galaxies may provide further hints on the possible presence of secular evolution and pseudobulge components.

The paper is organised as follows. After a brief summary of previous work in the literature on the stellar populations in bulges (Section 2), we will first present stellar population parameters ages, metallicities, and α/Fe ratios derived from Mg-, Fe- and the three Balmer line indices and compare them with the results of PS02 (Section 3). In Sections 4 and 5 we will confront bulges with early-type galaxies and derive star formation histories to quantify the amount and epoch of possible rejuvenation events. The results are discussed in Sections 6 and 7.

2 PREVIOUS AND CURRENT WORK

2.1 Colours

In the last decade, a number of papers have analysed colours of spiral bulges. Studying optical and near-infrared (near-IR) colour maps, Balcells & Peletier (1994) and Peletier et al. (1999) find that bulges of early-types are as old as elliptical galaxies, while smaller bulges in later-type spirals do show bluer colours and hence evidence for more recent star formation (see also MacArthur et al. 2004). In particular the steeper colour gradients in the latter point to the fingerprint of the galaxy disc and secular evolution of the bulge. This possibility is further supported by the finding that fainter bulges have exponential profiles (Carollo et al. 1998; Balcells et al. 2003), are more elongated (Fathi & Peletier 2003), and are more deeply embedded in their host disk than earlier type bulges (MacArthur, Courteau & Holtzman 2003). These properties clearly distinguish late-type bulges from both their counterparts in early-type spirals and elliptical galaxies, pointing to the presence of secular evolution in later-type systems.

2.2 Kinematics

The Fundamental Plane provides a similar picture. Even though no significant difference is found between bulge rotational properties and ellipticals with similar absolute magnitudes (Kormendy & Illingworth 1982; Davies et al. 1983) and ellipticals and bulges form a common major sequence in the κ-space, the latter are slightly offset indicating lower M/L ratios (Bender, Burstein & Faber 1992). This offset seems to increase going to later types (Falcón-Barroso, Peletier & Balcells 2002). These results imply that bulges and ellipticals must have had a common (or similar) formation epoch, while later type systems are increasingly affected by secular evolution. Chung & Bureau (2004) analyse boxy bulges in disc galaxies with types S0 to Sbc, and find a large fraction of bar-like structures pointing toward a formation processes involving disc material. Hence, both studies of colours and kinematics of bulges clearly support secular evolution models.

2.3 Absorption line indices - past

The situation becomes much more confused when absorption line index data are taken into consideration. Earlier work analysing Mg- and Fe-indices concludes that bulges are α/Fe enhanced just like elliptical galaxies (Bender & Paquet 1995; Fisher et al. 1996; Idiart et al. 1996; Jablonka et al. 1996; Casuso et al. 1996). Also recent results of the Ca triplet absorption around 8600 Å suggest no, or very small, differences between ellipticals and bulges: Falcón-Barroso et al. (2003) find that the latter seem to fit nicely into the CaT*-σ anti-correlation established by giant and dwarf elliptical galaxies (Saglia et al. 2002; Cenarro et al. 2003; Michielsen et al. 2003). At face value, these results suggest little difference between bulges and ellipticals, which works against the idea of secular evolution in terms of disc-triggered star formation. Still, details do reveal some interesting peculiarities. Bender & Paquet (1995) find that bulges of S0s show a large spread in Mg/Fe ratio, while the discs are mostly consistent with solar element ratios. Most interestingly, those bulges which have low Mg/Fe ratios also have younger ages. It seems this supports secular evolution. Note, however, that those results refer to lenticular galaxies, while secular evolution is expected to be increasingly important for bulges of later-type spirals (Kormendy & Kennicutt 2004).

2.4 Absorption line indices - present

Clearly, new data sets are needed. Three major projects, two of them yet to be completed, aiming at the study of bulges in spiral galaxies can be found in the current literature.

Trager, Dalcanton & Weiner (1999) plan to analyse a relatively large sample of 91 face-on spirals comprising a huge range of galaxy types from S0 to as late as Sdm. The sample includes both barred and unbarred spirals. Long-slit observations along both the major and the minor axes are carried out at the Las Campanas Observatory (6.5m) giving relatively high resolution (2 Å) in the $4000-5200$ Å region. First results derived from 10 objects indicate that massive bulges of earlier type spirals are old and metal-rich like elliptical galaxies, while the smaller bulges of later types appear younger and more metal-poor (Trager et al. 1999). These results are in line with the colour studies basically supporting secular evolution, but the role of contamination from disc light still needs to be assessed properly.

Goudfrooij, Gorgas & Jablonka (1999) and Jablonka, Gorgas & Goudfrooij (2002) have collected a sample of 28 spirals of types from S0 to Sc. Covering a similar wavelength range as the project above, exposure times of about 4h per object at a 4m-class telescope allow to study gradients of all important absorption features out to at least $1\ R_{\mathrm{e}}$. In contrast to Trager et al. (1999), these authors select edge-on spirals rather than face-on. The idea is that placing the slit along the minor axis of an edge-on spiral, one obtains the real gradient of the bulge, only the very central pixels being contaminated by disc light. In particular for gradient studies, this approach should be superior over the face-on data sample in disentangling bulge and disc components. In a first analysis, bulges are found to have similar ages and Mg/Fe ratios like ellipticals (Jablonka et al. 2002). Most interestingly, the index gradients measured are independent of the Hubble type

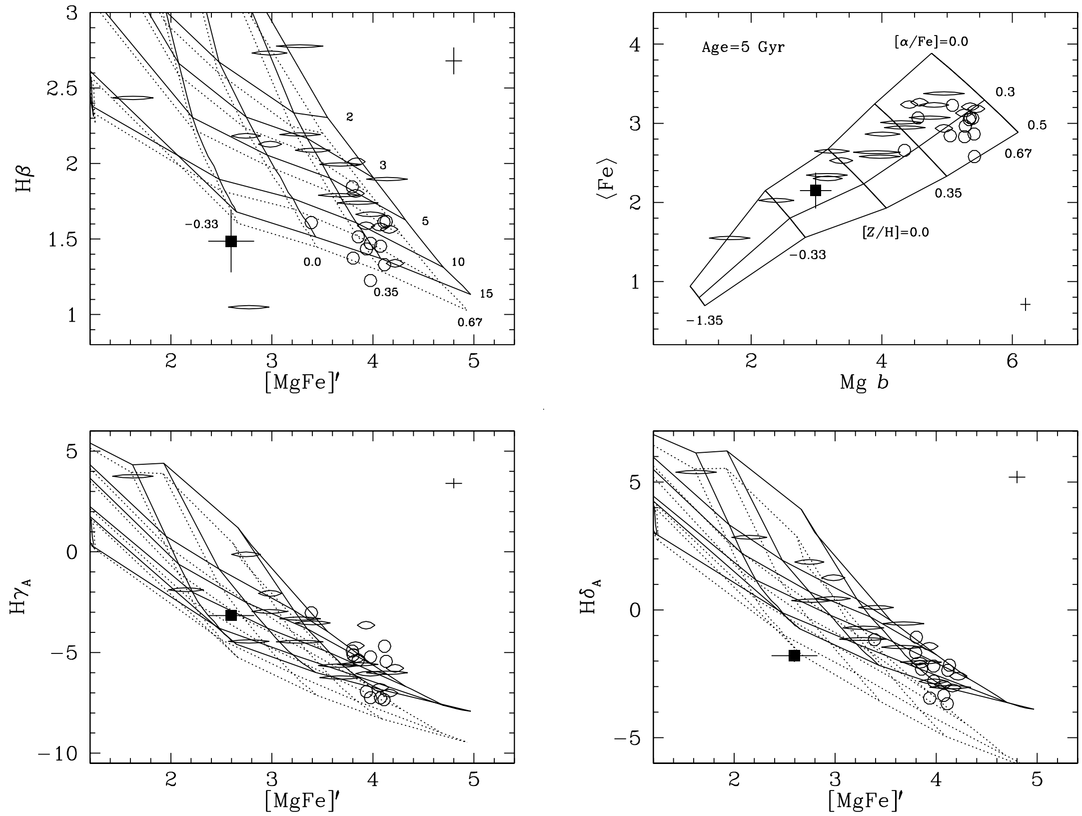

Figure 1. Lick absorption line indices (inner ~ 250 pc) of early-type galaxies (circles) and spiral bulges (ellipses with ellipticity increasing for the later types) from Proctor & Sansom (2002). The filled square is the integrated light of the Milky Way Bulge from Puzia et al. (2002). Stellar population models (Thomas et al. 2003, 2004) for various ages, metallicities, and α/Fe ratios (see labels) are over plotted. In the left-hand and the right-hand bottom panels dotted and solid lines are models with solar and enhanced ($[\alpha/\mathrm{Fe}] = 0.3$) abundance ratios, respectively. In the right-hand top panel age is fixed to 5 Gyr.

of the galaxy. These findings provide clear evidence against the secular evolution picture.

Finally, PS02 present a sample of 16 bulges in spirals with types Sa to Sbc, 6 lenticular and 11 elliptical galaxies. Like in the previous study, highly inclined targets are chosen. Slits are placed along the minor axes trying to avoid dust lanes, the wavelength range covered is similar to that of the studies above. The relatively modest exposure times ($\lesssim 1$ h) at a 4m-class telescope make this data sample less suitable for gradient studies. The main strength of this sample is the coverage of galaxy types, as the inclusion of lenticular and elliptical galaxies makes a very direct comparison with bulges possible. PS02 report both ages and α/Fe ratios of bulges to be lower than those in elliptical galaxies. A metallicity-mass relationship seems to be defined only by the bulges, and sharp differences between early and late-type bulges are apparent. These might be indication for secular evolution, even though this point is not discussed in the paper.

3 STELLAR POPULATION PARAMETERS

Fig. 1 presents the Lick absorption line indices Hδ_{A}, Hγ_{A}, Hβ, Mg b, and $\langle\mathrm{Fe}\rangle$ citepWoretal94,Traetal98 of the PS02 sample in comparison with the stellar population models of Thomas et al. (2003, 2004) for various ages, metallicities, and α/Fe ratios as indicated by the labels. The most important characteristic of these models is the inclusion of element abundance ratio effects using metallicity-dependent index response function calculated on high-resolution model atmospheres by Korn, Maraston & Thomas (2005). Open circles are early-type galaxies (ellipticals and S0s), bulges are the ellipses with ellipticity increasing for the later types. The filled square is the integrated light of the Milky Way Bulge (Puzia et al. 2002). These diagrams can already be used for first tentative conclusions on V-luminosity weighted ages and element abundances. The sample quite clearly forms an age sequence, bulges being both younger and less α/Fe enriched than ellipticals and S0s as already concluded by PS02 and most of the studies summarised in Section 2.

3.1 Balmer line indices and element abundance ratios

We want to draw the attention to another, more technical, but extremely important issue: the consistency of age estimates from the various Balmer absorption indices Hδ_{A}, Hγ_{A}, and Hβ. It is shown in Thomas et al. (2004) that the higher-order Balmer line indices (Worthey & Ottaviani 1997) become very sensitive to α/Fe element ratios at metallicities above solar. More specifically, the index strength significantly increases with increasing α/Fe ratio. The origin for this behaviour is the large number of Fe-lines lines in the pseudo-continua of the index definitions. A decrease of Fe abundance leads to a higher pseudo-continuum, and hence an increased index strength (Thomas et al. 2004; Korn et al. 2005). As the α/Fe enhanced models are characterised by a decrease in Fe abundance, this results in a positive correlation of index strength

and α/Fe ratio. It is demonstrated that with the inclusion of this effect, consistent ages are derived for the Kuntschner & Davies (1998) early-type galaxy sample from $\mathrm{H}\beta$ and $\mathrm{H}\gamma_\mathrm{A}/\mathrm{H}\gamma_\mathrm{F}$. Note that, the bluer the wavelength range considered, the more Fe lines perturb the Balmer index, and a larger abundance ratio effect is predicted (Thomas et al. 2004).

This can be appreciated in Fig. 1. The dotted and solid lines are models with solar and enhanced ($[\alpha/\mathrm{Fe}] = 0.3$) abundance ratios, respectively. While the size of the effect is comparable to the measurement errors and negligible for $\mathrm{H}\beta$, $\mathrm{H}\delta_\mathrm{A}$ clearly is most affected. Most importantly, the solar-scaled models (dotted lines) yield highly inconsistent age estimates from the three Balmer lines, a problem which disappears when the abundance ratio effect is taken into account (solid lines). A more quantitative comparison is presented in the following section.

3.2 Results from the various Balmer indices and PS02

We derive the luminosity weighted stellar population parameters age, metallicity, and α/Fe ratio from the metallic indices $\mathrm{Mg}\,b$, Fe5270, Fe5335 plus a Balmer line index ($\mathrm{H}\delta_\mathrm{A}$, $\mathrm{H}\gamma_\mathrm{A}$, or $\mathrm{H}\beta$) adopting the iterative procedure described in detail in Thomas et al. (2005). The aim of this section is to check consistency between the three Balmer indices and to confront the results with PS02. It should be noted beforehand that PS02 have corrected all three Balmer line indices for emission line filling adopting relationships between the Balmer and the [OIII] emission lines. Fig. 2 relates age (top panels), metallicity Z/H (middle panels), and α/Fe (bottom panels) derived using the higher-order Balmer line index $\mathrm{H}\delta_\mathrm{A}$ with the ones obtained with $\mathrm{H}\beta$ and $\mathrm{H}\gamma_\mathrm{A}$. The comparison with the results of PS02 is shown in the right-hand panels. Bulges are now plotted as filled circles without indicating the Hubble type to enhance the visibility of the plot. The dotted lines indicate identity.

3.2.1 $\mathrm{H}\delta_\mathrm{A}$ – $\mathrm{H}\beta$

Ages agree fairly well, but the scatter is large. For three bulges (NGC 4157, NGC 4217, NGC 4312) $\mathrm{H}\beta$ indicates significantly older ages, all three well above the age of the universe. Interestingly, exactly those objects show H_β emission greater than expected from [OIII] (PS02). Therefore their ages must clearly be overestimated, a problem by which the higher-order Balmer line $\mathrm{H}\delta_\mathrm{A}$ is much less affected. In these three cases $\mathrm{H}\beta$ yields metallicities that are too low in line with the overestimated ages. The cases in which H_β emission appears lower than expected from [OIII] (NGC 3254, NGC 3769, NGC 4313) do not exhibit any systematic deviation between $\mathrm{H}\beta$- and $\mathrm{H}\delta_\mathrm{A}$-ages, but display a particularly large scatter. Otherwise, metallicities agree well. The α/Fe is quite insensitive to these problems, the agreement is very good.

3.2.2 $\mathrm{H}\delta_\mathrm{A}$ – $\mathrm{H}\gamma_\mathrm{A}$

For the bulges, ages agree much better between $\mathrm{H}\gamma_\mathrm{A}$ and $\mathrm{H}\delta_\mathrm{A}$. In particular the emission line problems discussed above become much less severe, as expected, because $\mathrm{H}\gamma$ is significantly less affected by emission than $\mathrm{H}\beta$ (see PS02 and references therein). NGC 4157, NGC 4217, NGC 4312 still show slightly older ages from $\mathrm{H}\gamma_\mathrm{A}$, but the deviation approaches the general scatter in the relationship. For about half of the early-type galaxies the ages are systematically underestimated by $\mathrm{H}\gamma_\mathrm{A}$ with respect to $\mathrm{H}\delta_\mathrm{A}$. From Fig. 1 (bottom panels) it can be seen that these are the objects that scatter above the model grid in the $[\mathrm{MgFe}]'$-$\mathrm{H}\gamma_\mathrm{A}$ plane. However, perfectly consistent ages are derived for the other half. As there are no systematic differences in the stellar population parameters between the two groups, we interpret this deviation as observational scatter and a probable slight underestimation of observational errors. The younger ages of the 'deviating group' go along with slightly lower metallicities and significantly higher α/Fe ratios. The latter comes from the high sensitivity of $\mathrm{H}\gamma_\mathrm{A}$ to the abundance ratio. For the majority of the sample (including all bulges!), the estimates of both Z/H and α/Fe from the two higher-order Balmer lines agree very well with each other.

3.2.3 $\mathrm{H}\delta_\mathrm{A}$ – *PS02*

Finally, the right-hand panels in Fig. 2 show the comparison with the results of PS02. It is worth recalling here that PS02 do not use a specific Balmer line, but perform a minimum χ^2 fit to all 25 Lick indices. This approach can be considered fully complementary to ours. While we use only the few line indices that we understand and model very well, PS02 average out the ignorance of the detail by using the maximum possible information available. Hence it comes somewhat as a surprise that the ages derived here with $\mathrm{H}\delta_\mathrm{A}$, $\mathrm{Mg}\,b$, Fe5270, and Fe5335 agree so well with those of PS02. This result is highly reassuring and suggests that these two rather orthogonal methods yield correct results. This conclusion gets further support from the study of Proctor, Forbes & Beasley (2004), who find good consistency between the ages of globular clusters derived from the Balmer line indices separately and their minimum χ^2 method when using the Thomas et al. (2003) models (see their Fig. 5). There is some scatter in the ages of the early-type galaxies, which most likely is scatter in our age derivation caused by the combination of observational errors in $\mathrm{H}\delta_\mathrm{A}$ and the narrowness of the model grid at high metallicities (see Fig. 1). It should be emphasized that we obtain almost identical ages for all the objects with suspicious emission line patterns (see above), which had been responsible for deviations in $\mathrm{H}\beta$- and $\mathrm{H}\gamma_\mathrm{A}$-ages.

Likewise, metallicities agree. The α/Fe ratios are in reasonable agreement, and most importantly no systematic discrepancies are detected. This does not come as a surprise as in both the Thomas et al. (2003, 2004) models and the work of PS02 the incorporation of abundance ratios is based on a similar method (Trager et al. 2000a).

Still, some scatter is present, in particular for the bulges. These differences occur because the Thomas et al. models go into significantly more detail than the method used by PS02 based on the Vazdekis (1999) stellar population models. A major difference concerns the distinction of the various evolutionary phases for the inclusion of the index responses to abundance ratios variations from Tripicco & Bell (1995). These are given for dwarfs, turnoff stars, and giants. Thomas et al. apply these in the various phases separately before the final stellar population is synthesised. PS02, instead, apply the correction to the synthesised model weighting the index responses with a constant giant-turnoff-dwarf ratio of 53-44-3. The latter reflects the contributions to the flux continuum from the various evolutionary phases. Hence, this approximation does not account for the temperature and gravity sensitivity of the indices, which causes significant deviations from the giant-turnoff-dwarf ratio quoted above. For instance, as shown in Maraston et al. (2003), in a 15 Gyr old stellar population with solar metallicity, the dwarfs do contribute 20 per cent to the final Mg index, despite the low continuum flux. This contribution even increases to 60 per cent in the most metal-poor case.

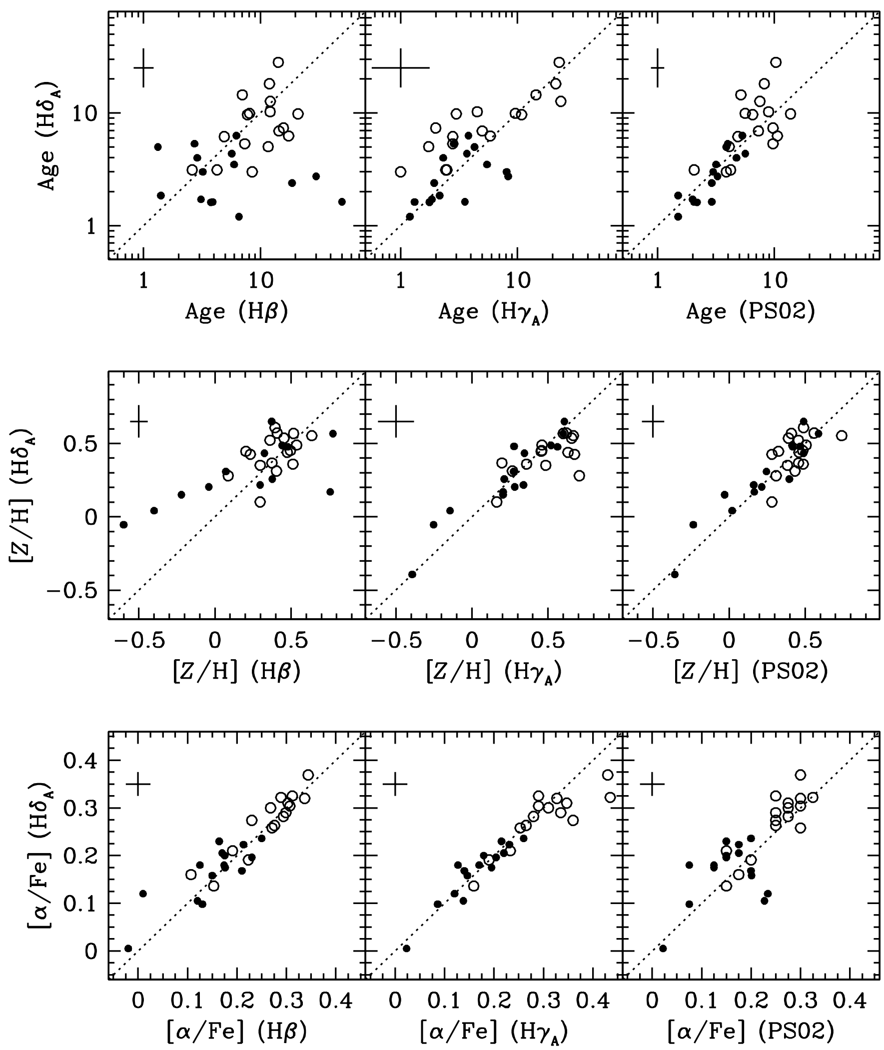

Figure 2. Comparison of the stellar population parameters age, metallicity, and abundance ratios derived from the H$\delta_{\rm A}$ as functions of those when Hβ or H$\gamma_{\rm A}$ are used instead. The right-hand panels show the comparison with the results from Proctor & Sansom (2002). Open circles are early-type galaxies, filled symbols are bulges.

A further strength of the Thomas et al. (updated) models is the use of the new index response function by Korn et al. (2005), which are calculated for the whole range of metallicities in contrast to Tripicco & Bell (1995), who are restricted to solar. To conclude, the scatter is most likely produced by the difference in the stellar population model adopted, the α/Fe ratios derived here based on the Thomas et al. models being more precise.

3.2.4 Relations with velocity dispersion

To put the comparison discussed above into a more scientific context, in Fig. 3 we plot the stellar population parameters resulting from H$\delta_{\rm A}$, H$\gamma_{\rm A}$, and Hβ separately as functions of velocity dispersion σ. A fourth panel shows the results of PS02.

Both PS02 and our H$\delta_{\rm A}$-ages display a very tight correlation with σ. The other two Balmer line indices yield the same relationship, but with significantly larger scatter. In particular some of the bulges with old Hβ-ages fall back on the relationship when H$\delta_{\rm A}$ is used instead. As mentioned earlier, those objects have indeed greater H$_\beta$ emission than expected from the [OIII] line, which results in an under correction and therefore an underestimation of the real Balmer line strength. In the other cases the emission line correction has obviously been successful but has significantly increased the systematic error and hence the scatter about the relation. The same holds for H$\gamma_{\rm A}$, as this index turned out to be as sensitive to the emission line problem as Hβ, because of a reduction in the continuum level (see PS02). H$\delta_{\rm A}$ is clearly to be preferred as age indicator, once the α/Fe effect is taken into account in the models. The extraordinary good consistency with the ages of PS02 further supports this conclusion.

Total metallicities derived from H$\gamma_{\rm A}$, H$\delta_{\rm A}$, and by PS02 agree well and show a clear correlation with σ. Only the metallicities obtained through Hβ seem not to be accurate enough to display this relationship. In case of the α/Fe ratios the situation is different.

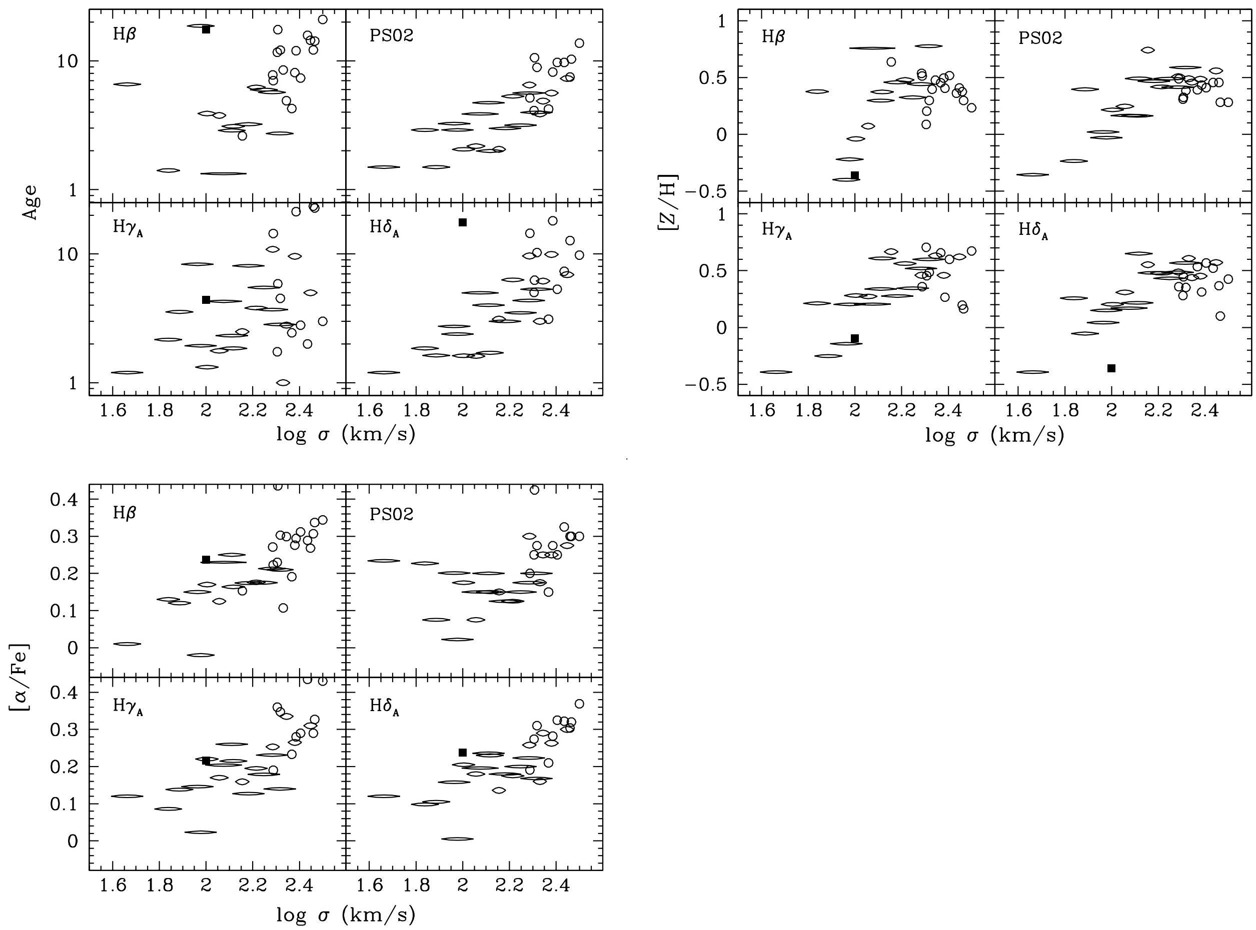

Figure 3. Comparison of the stellar population parameters age, metallicity, and abundance ratio obtained with various Balmer line indices (Hβ, H$\gamma_{\rm A}$, or H$\delta_{\rm A}$ as indicated by the labels) as age indicators as a function of velocity dispersion. A fourth panel shows the results of PS02. Circles are early-type galaxies, ellipses are spiral bulges with ellipticity increasing for the later types, and the filled square is the integrated light of the Milky Way Bulge. Errors are indicated in Fig. 2.

All three Balmer line indices yield clear α/Fe-σ relationships with comparable scatter, which is simply because the α/Fe ratio determination does not crucially depend on the derived age. The results of PS02 are in overall reasonable agreement with this. Except, PS02 find α/Fe ratios for NGC 3769 and NGC 4312 that are more than 0.1 dex higher than ours and seem relatively high given the low velocity dispersions of these objects. This discrepancy at the low-σ end dilutes the otherwise quite clear correlation between α/Fe ratio and σ in the PS02 results.

3.2.5 The Bulge of the Milky Way

The filled square in Fig. 3 shows the result for the integrated light of the Milky Way Bulge (line index data from Puzia et al. 2002). As shown in Maraston et al. (2003), the Bulge has relatively low Balmer line indices indicating a high luminosity weighted age and a low total metallicity (see Fig. 1), which significantly deviate from the age- and Z/H-σ relations found for the other bulges. Reasonable consistency is obtained only for the α/Fe ratio, as it depends only little on the Balmer line index. This result is in good agreement with the old ages and in reasonable agreement with the mean metallicity obtained by Zoccali et al. (2003) from a near-IR colour-magnitude diagram of the Bulge. However, the various Balmer indices do not provide consistent results. Puzia et al. (2002) measure a somewhat stronger H$\gamma_{\rm A}$, which yields younger ages (and hence higher metallicities) that would be in much better agreement with the rest of the bulges (Fig. 3). Most interestingly, this young 'H$\gamma_{\rm A}$-solution' is consistent with the parameters derived by Proctor et al. (2004) from the same data based on the χ^2 technique.

4 BULGES AND ELLIPTICALS IN COMPARISON

The sample of PS02 contains both bulges and early-type galaxies. A direct comparison between the two subsets clearly suggests that bulges are younger, less metal-rich and less α/Fe enhanced. However, the bulges in the sample have systematically lower central velocity dispersions σ, and very clear correlations of these three parameters with σ are evident. As all three parameters are known to correlate for early-type galaxy samples (e.g. Ferreras & Silk 2000; Trager et al. 2000b; Nelan et al. 2005; Thomas et al. 2005; Bernardi et al. 2005, and references therein), and it is not clear, whether the difference in the stellar population properties is simply the result of this relationship or whether it hints to different formation scenarios and disc influence in spiral bulges. A meaningful comparison as a function of Hubble type must certainly be carried out at a given σ.

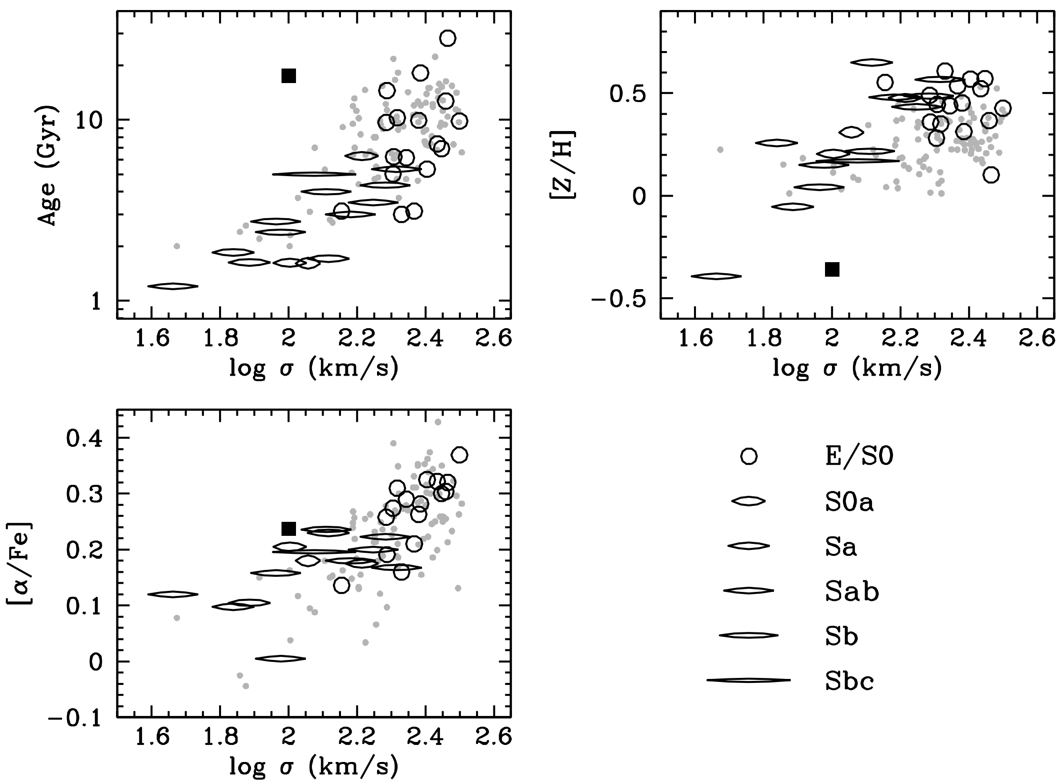

Figure 4. Stellar population parameters vs. velocity dispersion. Open circles are early-type galaxies from this work, ellipses are spiral bulges with ellipticity increasing for the later types (see labels in the right-hand bottom panel), and the filled square is the integrated light of the Milky Way Bulge. Small grey filled circles are early-type galaxies from Thomas et al. (2005). Central stellar populations are shown. Errors are indicated in Fig. 2.

In the following, we therefore confront the present results with the data of Thomas et al. (2005), in which stellar population parameters for a sample of early-type galaxies extending to relatively low velocity dispersion of around 100 km/s are derived. In Fig. 4 we plot age, total metallicity, and α/Fe ratio of both samples as functions of velocity dispersion. For the PS02 sample (open symbols), the results obtained with the higher-order Balmer index $\mathrm{H}\delta_\mathrm{A}$ (see previous section) are adopted, while $\mathrm{H}\beta$ is used in Thomas et al. (2005) (filled grey circles).

Before confronting the PS02 bulges with the low-mass early-type galaxies of Thomas et al. (2005), we check consistency at high velocity dispersion $\log\sigma > 2.3$ where both samples overlap in Hubble type. Ages and α/Fe ratios of the PS02 early-type galaxies (open circles) and the Thomas et al. (2005) objects (filled grey circles) indeed agree very well. Metallicities of the PS02 objects are higher by about 0.1 dex, which most likely is an aperture effect. While PS02 use a fixed central aperture of 3.6×1.25 arcsec^2, Thomas et al. (2005) consider a variable aperture that ensures the coverage of 1/10 of the effective radius. Hence, for large objects, PS02 sample a more centrally concentrated fraction of the stellar population. Given the presence of a negative metallicity gradient in early-type galaxies (Davies et al. 1993; Carollo & Danziger 1994; Fisher et al. 1995; Saglia et al. 2000; Mehlert et al. 2003; Wu et al. 2005), this explains the slight offset between PS02 and Thomas et al. (2005). Such an offset caused by aperture effects is not to be expected in age and α/Fe ratio, because early-type galaxies are found to have no gradients in these parameters (Davies et al. 2001; Mehlert et al. 2003; Wu et al. 2005). Ages and α/Fe ratios of the two samples indeed agree very well.

A similarly good consistency between the samples is evident also in the low velocity dispersion regime ($\log\sigma \sim 2$). Low-mass early-type galaxies and bulges appear to obey the same relationship of age and α/Fe ratio with σ. Spiral bulges and low-mass early-type galaxies host stellar populations with the same young luminosity weighted ages around 2–3 Gyr. In line with these, both types of objects display low α/Fe ratios of about 0.1 dex reinforcing the presence of recent star formation suggested by the young ages. Metallicities agree at low σ, which is simply due to the fact that the smaller aperture of PS02 in smaller objects samples a larger proportion of light more consistent with Thomas et al. (2005). To conclude, the very prominent correlations of age, metallicity, and α/Fe with velocity dispersion found for spiral bulges holds also for early-type galaxies.

5 STAR FORMATION HISTORIES

The relationships age-σ and Z/H-σ given in Thomas et al. (2005) are significantly flatter than what is inferred from Fig. 4, because they are derived for objects with σ well above 100 km/s. As shown in Thomas et al. (2005), the inclusion of low-mass objects steepens the correlations for early-type galaxies significantly (see also Smith 2005). Indeed, in Thomas et al. (2005) the low-mass end of the sample is best reproduced assuming the occurrence of a minor (~ 10 per cent) recent (~ 1 Gyr ago) episode of star formation.

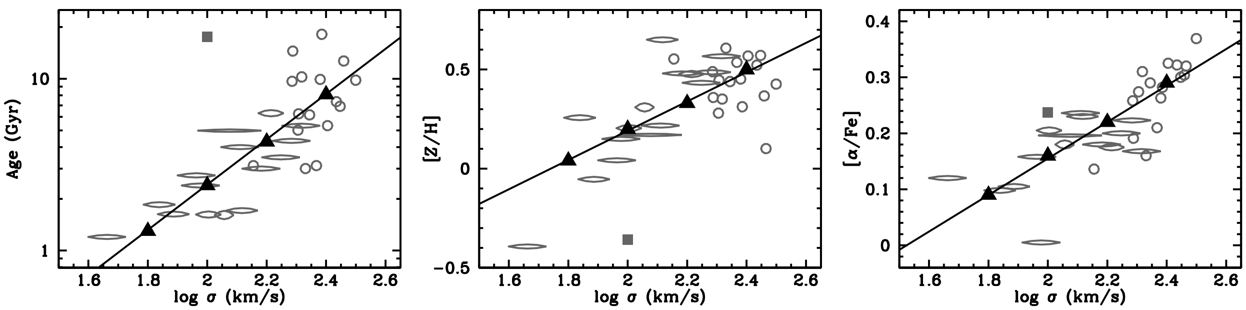

Figure 5. Stellar population parameters as function of velocity dispersion. Triangles are composite models considering the presence of a young subcomponent over an underlying old population (see Fig. 6). Grey symbols are the observational data points from Fig. 4.

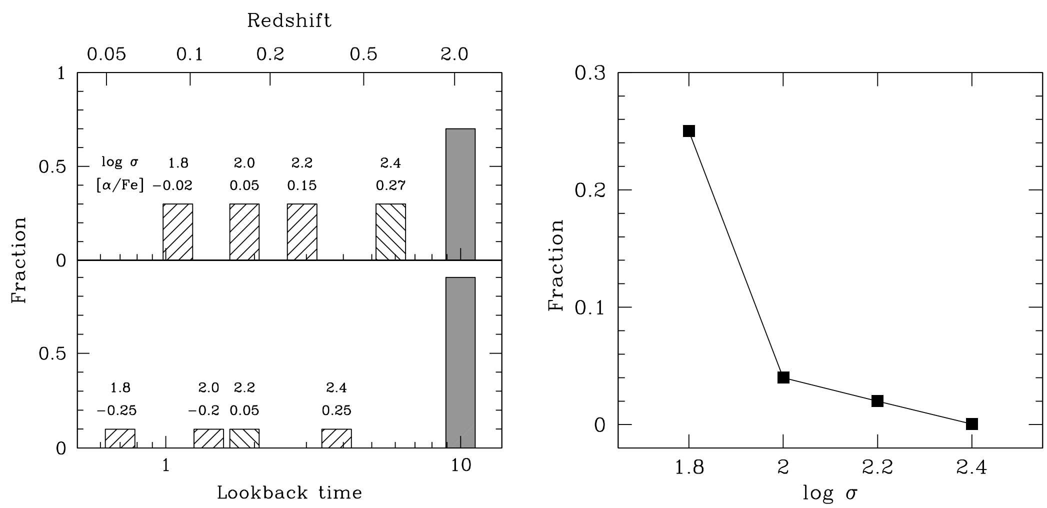

Figure 6. Two-component star formation histories that reproduce the observed relationships between stellar population parameters and velocity dispersion (see triangles in Fig. 5). An underlying old population with a formation redshift $z_{\rm f} \sim 2$ is perturbed by a young sub-component. *Left-hand panel*: The mass fraction of the secondary component (hatched rectangles) is fixed to 30 panel (top panel) and 10 per cent (bottom panel), formation redshift is varied. Plotted are the mass fractions of the two components as functions of look-back time and redshift ($\Omega_{rmm} = 0.2,\ \Omega_\Lambda = 0.8,\ H_0 = 72$ km/s/Mpc). Labels give the associated velocity dispersions of the various realisations and the $\alpha/$Fe ratio of the young population. *Right-hand panel*: The formation redshift is fixed to $z \sim 0.08$ (corresponding to a look-back time of 1 Gyr), and the mass fraction of the young component is varied. The plot shows this mass fraction as a function of velocity dispersion.

5.1 Model parameters

Similar in spirit to de Jong & Davies (1997), in the following we explore how the luminosity weighted ages and the above relationships can be reproduced by star formation histories characterised by secondary star formation on top of a dominating, underlying old population. We assume this latter base population to have an age of 10 Gyr corresponding to a formation redshift of $z \sim 2$, and to have an abundance ratio $[\alpha/\mathrm{Fe}] = 0.3$ dex, reflecting a rapid formation process (see Thomas et al. 2005). As we cannot constrain the mass contribution from a secondary burst, we test three options: two in which we fix the mass contribution of the recent star forming event to 10 and 30 per cent, respectively. In these two models we then vary as a free parameter the look-back time at which the secondary burst must have happened, in order to match the luminosity weighted age. In the third model we fix the look-back time to 1 Gyr and vary, instead, the mass fraction of the secondary population.

In general, the $\alpha/$Fe ratio of the secondary population is varied such that the $\alpha/$Fe-σ relationship of Fig. 4 is reproduced. For simplicity, metallicity is assumed to be the same for both the base old and the secondary population, and is chosen such that consistency with the correlation of Fig. 4 is ensured. This approach makes the sensible assumption that velocity dispersion (hence total mass) of the object determines the total metallicity of the entire population. The age and element abundance ratio, instead, are considered to be σ-dependent for the secondary burst and universal for the base population. This prior needs to be set, in order to avoid underdetermination of the problem. From the Balmer line index and the two metal indices we derive age (for the first two options) or burst fraction (for the third option) and $\alpha/$Fe ratio of the secondary population, which are the main focus of this study. As a third parameter we obtain the metallicity of both components, which we need for consistency reasons.

The stellar population parameters of the synthesised population are determined as follows: first we compute line indices (H$\delta_{\rm A}$, H$\gamma_{\rm A}$, Hβ, Mg b, Fe5270, Fe5335) of the two-component population. These are obtained by summing up the fluxes in the pseudo-continua and line windows, out of which the final index value is

calculated as described in, e.g., Maraston et al. (2003). From these mock observables we determine stellar population parameters. In this way we ensure that luminosity weighted quantities are obtained. The input parameters described above are iteratively modified until observations as presented in Fig. 4 are reproduced.

5.2 Consistency of the three Balmer indices

It should be noted that the three Balmer line indices are considered separately. As $H\delta_A$ is located at a bluer part of the spectrum, it responds to slightly hotter temperatures than $H\beta$. As a consequence, a composite stellar population with hot sub-components must lead to different age estimates from these two indices. The size of the effect, however, depends strongly on the turnoff temperature (hence the age) of the young component. In the previous section (see Fig. 3) it is shown that consistent age estimates are obtained. The present simulations allow us to quantify this effect and to test whether these consistent age estimates exclude the presence of a hot sub-component.

The effect is maximum for a 1 Gyr sub-component, where the turnoff temperature hits exactly the wavelength of the $H\delta$ line. We find that around this maximum, $H\delta_A$ yields luminosity weighted ages that are about $10-20$ per cent, i.e. $0.05-0.08$ dex, younger compared to $H\beta$. Fig. 4 shows that this difference is too small to be detected with the present data set. It should be emphasized that even younger subpopulations, as recently found by Yi et al. (2005) in some fraction of early-type galaxies on the basis of GALEX photometry, would not affect the consistency of the ages estimated from $H\beta$ and $H\delta$ as their turnoff temperatures are hotter than both $H\beta$ and $H\delta$.

5.3 Results

Fig. 5 shows the stellar population parameters of the models described above as filled triangles in comparison to the observational data (grey symbols). We produced models for $\log\sigma = 1.8,\ 2.0,\ 2.2$ and 2.4, that – by construction – match the observed correlations with velocity dispersion.

The star formation histories of these models are illustrated in Fig. 6. The left-hand panel shows the first two options, in which the look-back time of the secondary burst is modified. The grey filled histogram is the underlying old population with a formation redshift of $z_f \sim 2$. The hatched histograms show the ages of the young sub-components (labels are velocity dispersions and α/Fe ratios). If we assume the young population to contribute 10 per cent to the total mass, the ages measured here for spiral bulges and low-mass early-type galaxies require recent star formation at redshifts between $z \sim 0.05$ and 0.5, corresponding to look-back times between 0.7 and 4 Gyr. Assigning 30 per cent of the total mass to the young sub-component moves these quantities only mildly to higher look-back times as shown by the top panel. The lower σ, the more recent is the required star formation. And the more recent the additional star formation, the lower the α/Fe ratio of the young component as a larger time span allows Fe enrichment from Type Ia supernovae (Fig. 6).

Alternatively, if we fix the formation redshift of the young population, its mass fraction must increase with decreasing σ (model 3). This is shown by the right-hand panel of Fig. 6, in which the fraction of the secondary component is plotted as a function of σ. The contributions in mass from a 1-Gyr subcomponent increase from only 0.05 per cent for $\log\sigma = 2.4$ to as much as 25 per cent for the smallest bulges.

6 DISCUSSION

We analyse the central (inner ~ 250 pc) stellar populations of bulges in spiral galaxies with Hubble types Sa to Sbc by re-deriving luminosity weighted ages, metallicities, and α/Fe ratios of the PS02 sample. We find that all three stellar population parameters display very clear positive relationships with central velocity dispersion. Our results confirm the previous finding of PS02 and, in particular, improve upon the correlation with α/Fe ratio. Lower-mass bulges have younger luminosity weighted ages and lower α/Fe ratios, both hinting toward the presence of extended star formation. These results are in line with the findings of previous studies based on colours and absorption line indices as summarised in Section 2. We note that the relatively young age (5 Gyr) derived for the bulge of the S0 galaxy NGC 7332 ($\log\sigma \sim 2.15$) by Falcón-Barroso et al. (2004) fits perfectly in the age-σ relationship shown here. In contrast, Sarzi et al. (2005) find predominantly old stellar populations in the very centres (inner ~ 8 pc) of spiral bulges, which might be caused by the fact that the central black hole prevents star formation in its immediate vicinity.

6.1 Bulges – just like low-mass ellipticals

We show that the occurrence of recent secondary star formation episodes involving about 10–30 per cent of the total mass at look-back times between ~ 0.5 and 5 Gyr, corresponding to the redshift interval $0.05 \lesssim z \lesssim 0.5$, provide a suitable explanation for the above relationships. The weight of the recent star formation event, either in terms of formation redshift or mass fraction, increases with decreasing bulge velocity dispersion. If we keep in mind that low σ characterises pseudobulges, this may indicate that secondary evolution in bulges triggered by disc instabilities as suggested by Kormendy & Kennicutt (2004) does take place, predominantly in low-mass objects. On the other hand, the stellar population properties derived in this paper do not depend on Hubble type, which complements the previous findings that disc and bulge scale lengths as well as bulge to disc ratios correlate with bulge luminosity rather than with Hubble type (de Jong 1996; Courteau, de Jong & Broeils 1996; Balcells, Graham & Peletier 2006). This, in contrast, hints to an independent formation of the bulge rather than secular evolution.

How can we resolve this apparent contradiction, and, more importantly, how can we get further hints about the process at work? If the evolution of the stellar populations in spheroids with discs around them, i.e. bulges of spiral galaxies, is affected by the presence of the disc, then spheroids without discs, i.e. elliptical galaxies, should exhibit different properties. We therefore compare in this paper the present results with the stellar population properties of early-type galaxies (Thomas et al. 2005). It is shown in a number of studies, that elliptical galaxies also obey a correlation between luminosity weighted age and mass in the sense that low-mass galaxies are affected by late star formation (e.g. Ferreras & Silk 2000; Trager et al. 2000b; Nelan et al. 2005; Thomas et al. 2005; Bernardi et al. 2005; Cappellari et al. 2006, and references therein).

We find that bulges are generally younger than early-type galaxies, because of their smaller masses. Bulges and early-type galaxies exhibit the same correlation between their stellar population properties and mass. In other words, at a given σ, we find no difference between bulges and ellipticals, they are indistinguishable objects as far as their basic stellar population properties are concerned. Hence, Hubble type does not determine the stellar populations of spheroids in a large range of Hubble type from E to at least Sbc, which is the latest type probed in the present study. The disc

does not significantly affect the bulge's stellar populations. Bulges, like low-mass ellipticals, are rejuvenated, but not by secular evolution processes involving disc material. It should be emphasized that bulges with dust lanes (like e.g., NGC 4157), that are the most promising candidates for pseudobulges, also obey these relationships. Hence, secular evolution and pseudobulges can only play a role in spiral galaxies with types later than Sbc.

The picture of rejuvenation of bulges fits in well with the finding that bulges are bluer than ellipticals at any given redshift out to $z \sim 1$ (Ellis, Abraham & Dickinson 2001). Our results provide a clearer insight into this. Ellis et al. (2001) find that bulges are bluer because they have both younger ages and lower metallicities than the ellipticals in the sample, which in turn is the simple consequence of their lower velocity dispersions (or total masses). Indeed, in their Fig. 4 ellipticals with lower galactic concentration are as blue as the bulges at any redshift. It is intriguing that the observed near-IR $J-H$ colours of the bulges are redder at $z \gtrsim 0.5$, and similar to those of ellipticals at redshifts below 0.5. The redder near-IR colour might be connected to the TP-AGB star population present in stellar populations with ages between 0.1 and 2 Gyr (Maraston 2005), but we cannot think of any reasonable star formation history for which this effect should disappear below $z \sim 0.5$. On the contrary, it should even be more pronounced there, because the observed near-IR colour shifts more toward rest-frame near IR, where the effect of the TP-AGB is strongest. A more detailed investigation of this issue would be interesting, but by far exceeds the scope of this paper.

6.2 Caveats and open questions

A general concern about probing the central stellar populations in the bulge of a disc galaxy is the contamination from disc material in the line of sight. Based on observed bulge-to-disc ratios of edge-on spirals of type not later than Sbc (Khosroshahi, Wadadekar & Kembhavi 2000), PS02 argue that the disc contamination cannot exceed the 10 per cent level in light. Because of the relatively young luminosity weighted ages derived (consistent with PS02), the contribution of the young subpopulation exceeds this upper limit by far. In other words, the young ages found for bulges cannot be artifacts from projected young disc stars. If disc contamination was artificially lowering the derived ages, bulges would by inference be older than ellipticals at a given σ, which would argue strongly against secular evolution.

There is another intriguing problem. The bulge of our own galaxy is known to be old (Renzini 1999). Zoccali et al. (2003) analyse near-IR colour magnitude diagrams of large, statistically meaningful, bulge fields. They derive an age larger than 10 Gyr and find no trace of any younger stellar population. Interestingly, this result is perfectly consistent with the luminosity weighted age that we derive in this paper (see the square in Fig. 4). Also the sub-solar metallicity we derive is consistent with the metallicity distribution derived by Zoccali et al. (2003). However, these values are deviant from the general ages and metallicities of bulges. Our bulge appears significantly older and more metal poor. This is certainly an odd situation.

In the present work, the old age for our bulge is derived from the $\mathrm{H}\delta_\mathrm{A}$ Balmer line index, and is consistent with the age obtained from $\mathrm{H}\beta$ (see Fig. 3). However, $\mathrm{H}\gamma_\mathrm{A}$ suggests a considerably younger age of about $4-5$ Gyr, which would then be consistent with the age-σ relationship of the other bulges. The metallicity would be slightly higher, and hence also more consistent with the derived relationship. It is possible that the measurements of both $\mathrm{H}\delta_\mathrm{A}$ and $\mathrm{H}\beta$ are corrupted, and that the younger age implied by $\mathrm{H}\gamma_\mathrm{A}$ gives the correct result. This view is supported by the similarly young age derived by Proctor et al. (2004) from the same data based on their χ^2 technique. Note that the latter is quite insensitive to uncertainties of individual absorption line indices. This analysis suggests that the bulge of the Milky Way is not special.

However, there is then a clear contradiction with the work of Zoccali et al. (2003). Their conclusion is certainly robust, and the only caveat that affects their non-detection of young stellar populations is the correction from the contamination of foreground disc stars. Even though this is done very carefully using a large disc control field, an overcorrection that 'removed' young bulge stars cannot be entirely excluded. Alternatively, the apparent conflict with the old age found by Zoccali et al. (2003) might be resolved if there was a population gradient. The PS02 data and Puzia et al. (2002) data for the bulge sample the central region, the inner ~ 250 pc, while the fields observed by Zoccali et al. (2003) are approximately 1 kpc from the centre. A rejuvenation of the centre of our bulge would indeed fit with the fact that young stars and star clusters are found in the very centre (Figer et al. 1999; Genzel et al. 2003). If significant, this would imply that bulges have positive age gradients, in contrast to early-type galaxies for which no age gradients are detected (Davies et al. 2001; Mehlert et al. 2003; Wu et al. 2005). Detailed studies of the gradients in bulges may help in future to solve this issue (Jablonka et al. 2002).

7 CONCLUSIONS

The main aim of this paper is to investigate whether the evolution of the stellar population in bulges is modified by the presence of the disc. We seek to understand whether secular evolution, and maybe the formation of pseudobulges, play an important role in the evolution of spiral galaxies. Our approach is to compare the stellar population properties in bulges with those in elliptical galaxies at a given central velocity dispersion, hence spheroid mass.

For bulges, a suitable sample is PS02 comprising 16 bulges in spirals with types Sa to Sbc, 6 lenticular and 11 elliptical galaxies. We derive luminosity weighted ages, metallicities, and α/Fe ratios from one Balmer line index ($\mathrm{H}\delta_\mathrm{A}$, $\mathrm{H}\gamma_\mathrm{A}$, or $\mathrm{H}\beta$ considered separately), and the metallic indices $\mathrm{Mg}\,b$, Fe5270, and Fe5335 using the element ratio sensitive stellar population models of Thomas et al. (2003, 2004). As there is relatively little overlap in σ between the bulges and the early-type galaxies in the PS02 sample, we compare the results with the sample of Thomas et al. (2005), which contains elliptical galaxies with velocity dispersion as low as 50 km/s. For both samples we obtain very clear relationships between all three stellar population parameters and σ.

Thomas et al. (2004) demonstrate that the higher-order Balmer line indices are very sensitive to element ratios effects, and that consistent age estimates from $\mathrm{H}\beta$ and $\mathrm{H}\gamma_\mathrm{A}$ are obtained only when these effects are taken into account in the models. Here we extend this exercise to $\mathrm{H}\delta_\mathrm{A}$, as the PS02 sample includes also this index. We obtain very consistent estimates of ages, metallicities, and α/Fe ratios from the three Balmer line indices. Emission line filling plays a critical role, impacting crucially on the scatter of the derived age-σ relation. The latter is smallest for $\mathrm{H}\delta_\mathrm{A}$. Importantly, the ages and metallicities derived here using $\mathrm{H}\delta_\mathrm{A}$ are extraordinarily consistent with those given by PS02. Note that PS02 do not use a specific Balmer line, but perform a minimum χ^2 fit to all 25 Lick indices, an approach fully complementary to ours. While

we use only the few line indices that we understand and model very well, PS02 average out the ignorance of the detail by using the maximum possible information available. The excellent consistency found here is reassuring and suggests that these two rather orthogonal methods yield correct results. It should be emphasized that the χ^2 method is not dominated by the particular line indices used in the present study.

In agreement with other studies, we find that bulges have relatively low luminosity weighted ages, the lowest age derived being 1.3 Gyr. Hence bulges are not overall old, but are actually rejuvenated systems. Interestingly, there is evidence that the bulge of the Milky Way also fits into this picture. We find clear correlations of all three parameters luminosity weighted age, total metallicity, and α/Fe ratio with central velocity dispersion, the smallest bulges being the youngest with the lowest α/Fe ratios owing to late Fe enrichment from Type Ia supernovae. We construct composite models in which a young subcomponent is superimposed over an underlying old population, in order to constrain the epoch and mass fraction of the rejuvenation event. We show that the smallest bulges must have experienced significant star formation events involving $10-30$ per cent of their total mass in the past $1-2$ Gyr. Curiously, these results are not consistent with the age estimates for the Bulge of the Milky Way in the literature, which appears to have an overall old stellar population and no traces of recent star formation. We discuss new evidence that at least the central ~ 500 pc of the Milky Way bulge contains a significant fraction of young stellar populations.

The comparison with the Thomas et al. (2005) sample reveals that the above relationships with σ coincide perfectly with those of early-type galaxies. In other words, bulges are typically younger, metal-poorer and less α/Fe enhanced than early-type galaxies, only because of their smaller masses. At a given velocity dispersion, bulges and elliptical galaxies are indistinguishable as far as the basic properties of their stellar populations are concerned. No significant correlations of the stellar population parameters with Hubble Type as late as Sbc are found, instead. In other words, the stars in bulges do not originate in the discs. This result also agrees with the finding that structural parameters like disc and bulge scale lengths, as well as bulge-to-disc ratios, are correlated with bulge luminosity rather than with Hubble type.

If central spheroids have the same properties in galaxies with and without discs, this clearly favours inside-out galaxy formation (van den Bosch 1998) according to which the disc forms after the bulge. Models that aim to explain the formation of bulges through disc fragmentation processes need to push the formation epoch to relatively high redshifts assuming high dissipation efficiencies (Immeli et al. 2004). Only in spiral galaxies of Hubble types later than Sbc discs can have a significant influence on the evolution of the stellar populations in the bulge component. This fits with the fact that Sersic index drops significantly in the transition between Hubble types Sbc and Sd (Balcells et al. 2006). Secular evolution through the disc and the phenomenon of pseudobulge formation is most likely restricted to spirals of types Sc and later.

ACKNOWLEDGEMENTS

Claudia Maraston, Robert Proctor, and Marc Sarzi are thanked for very constructive discussions. The referee is acknowledged for the very careful and constructive report. This project has been partly supported by grant BMBF-LPD 9901/8-111 of the Deutsche Akademie der Naturforscher Leopoldina.

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